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# The Effect of Timing Jitter on a 160-Gb/s Demultiplexer

Darko Zibar, Leif K. Oxenløwe, Hans C. H. Mulvad, Jesper Mørk, Michael Galili, Anders T. Clausen, and Palle Jeppesen

**Abstract**—For high-speed optical communication systems, timing jitter is a crucial parameter for switching operations between the data and control signal. This is especially the case for the demultiplexer. The effect of timing jitter becomes very important as the bit rate of the data signal increases beyond 100 Gb/s and it is, therefore, essential to quantify its effect. In this letter, the impact of gating timing jitter on a 160-Gb/s demultiplexer is investigated by using two pulse sources with different timing jitter properties. We also investigate the interplay between the control signal pulsewidth and timing jitter. The experiment shows that it is essential to minimize jitter in the 20-kHz to 10-MHz range. Furthermore, we show that the impact of timing jitter can be reduced if the control signal pulses are broader than data signal pulses.

**Index Terms**—Demultiplexing, high-speed, optical communication, optical time-division multiplexing (OTDM), pulsewidth, timing jitter.

## I. INTRODUCTION

**D**UE TO the rapid growth of broadband services, the demand for higher data capacities is growing. Ultrahigh-speed optical communication systems have once again started to attract considerable attention from industry and universities alike. This has resulted in a race to increase single-channel bit rate. A good example of this trend is the recent work on 100-Gb/s electrical time-division-multiplexed systems and ethernet [1], [2]. Moreover, electronics are currently reaching speeds of 160 Gb/s [3], but many challenges still remain to be met. One of these challenges is high power consumption and complexity which increases significantly as the data bit rate is increased. The most efficient way to realize ultrahigh-speed single-channel optical transmission systems is still to use optical time-division multiplexing (OTDM). OTDM systems can be used to generate single-channel data systems up to 640 Gb/s [4], [5]. However, the challenge associated with such high-speed OTDM systems is demultiplexing to lower bit rates. In order to demultiplex the high-speed signal, an ultrafast all-optical switch is needed. There are two main ways to perform optical demultiplexing: using semiconductor or fiber-based solutions. However, as the bit rate is increased significantly, a fiber-based demultiplexer is a very promising solution due to its very high-speed operation. Furthermore,

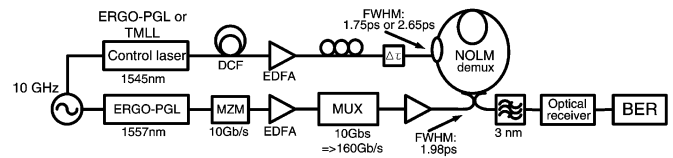


Fig. 1. Experimental setup used to investigate the effects of data to control signal timing jitter on NOLM switching BER performance.

using the fiber-based demultiplexer, the effect of amplified spontaneous emission (ASE) is avoided.

On numerous occasions, a nonlinear optical loop mirror (NOLM) has shown great potential for providing ultrafast switching, due to the ultrafast optical nonlinear response associated with fibers [4]. As the data signal bit rate is increased, timing jitter requirements on the data and control signal become more demanding for the demultiplexing operation [6]. It has been shown theoretically that relative timing jitter between the data and control signal degrades the bit-error-rate (BER) performance [6], [7]. However, the impact of timing jitter has only been investigated experimentally at the line rate of 2.5 and 20 Gb/s, where the jitter requirements are modest. In this letter, we experimentally investigate the effects of timing jitter on an NOLM-based demultiplexer at 160 Gb/s. We use two pulse sources for control signal generation with different timing jitter properties. Furthermore, the two pulse sources considered have different mechanisms to synchronize with an external clock signal and this influences the demultiplexing performance. In addition, we investigate the interplay between the control signal pulse width and timing jitter to achieve error-free performance of the system.

## II. EXPERIMENTAL SETUP

The experimental setup used to generate a 160-Gb/s OTDM data signal and to demultiplex the data signal to 10 Gb/s is shown in Fig. 1.

The optical data signal is generated by a solid state mode-locked erbium glass oscillator pulse generating laser (ERGO-PGL) at 10 GHz and 1557 nm. The ERGO-PGL uses an internal phase-locked loop (PLL) in order to obtain synchronization with a reference clock. The integrated timing jitter of ERGO-PGL transmitter laser is  $\sim 90$  fs. The data signal pulses are externally modulated with a pseudo-random bit sequence (PRBS) with a length of  $2^7 - 1$  using a Mach-Zehnder modulator and injected into a high-power erbium-doped fiber amplifier (EDFA). The pulses generated from the ERGO-PGL at the transmitter are approximately 2 ps wide. The 10-Gb/s data signal is then multiplexed to 160 Gb/s

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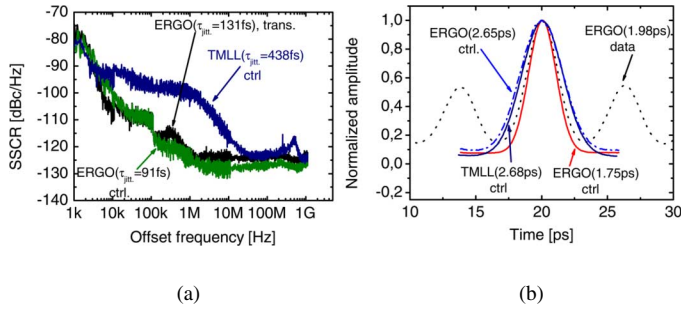


Fig. 2. (a) SSCR of the data and control signal pulse sources measured at the input of NOLM. Jitter integration range: 20 kHz–80 MHz. (b) Autocorrelation traces of the data and control signal pulses at 160 Gb/s and 10 GHz, respectively, measured at the input of the NOLM.

by a passive fiber delay polarization and PRBS maintaining multiplexer. The 160-Gb/s data signal is further amplified by an EDFA to 15 dBm before being injected into the NOLM. For the control pulses required to demultiplex the 160-Gb/s signal, we have tested two different types of pulse sources: a solid state ERGO-PGL (similar to the one at the transmitter) and an external cavity semiconductor tunable mode-locked laser (TMLL). The ERGO-PGL and TMLL used to generate control signal pulses have different phase noise (timing jitter) properties. The full-width at half-maximum (FWHM) of the control signal pulses is varied (2.68 and 1.75 ps) in order to investigate the performance of the NOLM-gate dependence of control signal pulsewidth and timing jitter at high bit rates. The data and control signal pulses are synchronized to the same synthesizer. The wavelength of the control signal pulses is kept constant at 1545 nm. The highly nonlinear fiber used in the NOLM is a 500-m commercially available fiber with a relatively flat dispersion slope (zero dispersion  $\sim 1551$  nm, slope  $\sim 0.017$  ps/nm<sup>2</sup>,  $\gamma \sim 10$  W<sup>-1</sup> · km). Finally, after the demultiplexing, the 10-Gb/s signal is sent through a 3-nm optical bandpass filter to filter out control pulses and it is then injected into a preamplified 10-Gb/s receiver for BER evaluation.

### III. SIGNAL CHARACTERIZATION

In Fig. 2(a), the single sideband-to-carrier ratio (SSCR) of the data and control signal pulse sources are shown. It is observed that the data signal SSCR curve ( $\tau_{\text{jitt}} = 131$  fs) and control signal SSCR ( $\tau_{\text{jitt}} = 91$  fs, ERGO-PGL) follow each other closely as was expected (they are synchronized to the same clock source). The reason for the slight increase in the data signal jitter is due to multiple EDFA amplification.

Fig. 2(a) shows that the TMLL exhibits more phase noise in the 20-kHz to 10-MHz range than the ERGO-PGL pulse sources. This is because the modulation bandwidth of the TMLL is relatively large (1 MHz), allowing the phase noise from the reference (synthesizer) signal to be directly transferred, and also because the TMLL itself is noisy due to ASE. The ERGO-PGL lasers use an internal PLL, with a bandwidth of only 10 kHz, in order to obtain synchronization with the reference signal. In this way, the phase noise contribution from the reference signal is filtered out. Furthermore, the ERGO-PGL itself has low noise at frequencies exceeding the PLL bandwidth.

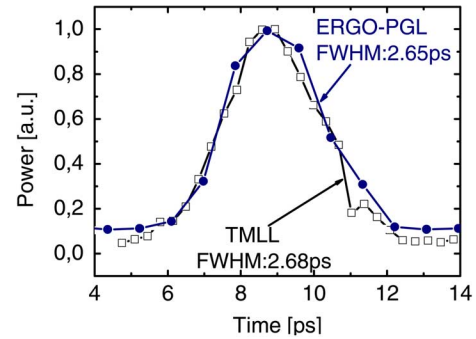


Fig. 3. Measured switching windows when the ERGO-PGL and TMLL are used as control pulse sources.

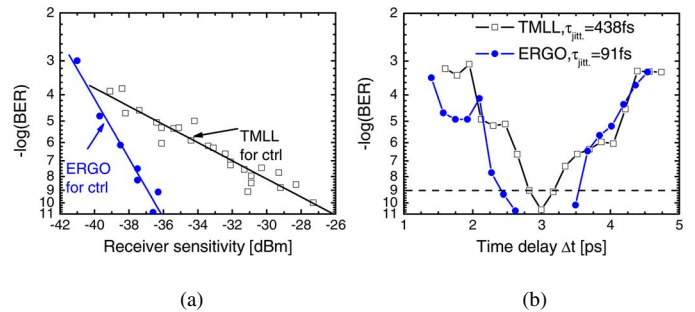


Fig. 4. (a) Measured BER curves for the demultiplexed 10-Gb/s signal. FWHM of the controls signals: 2.65 ps. (b) BER as a function of relative time delay between data and control signal pulses.

By using the ERGO-PGL and TMLL as control signal pulse sources, the impact of excess jitter in the range from 20 kHz to 10 MHz is investigated. In Fig. 2(b), autocorrelation traces of the data signal together with the control signal pulses are shown. Clean and smooth autocorrelation traces of the 160-Gb/s data signal pulses with FWHM of 1.98 ps (deconvolved pulse) are observed. Fig. 2(b) also contains the autocorrelation traces for the ERGO-PGL control signal laser source with an FWHM of 2.65 ps (deconvolved pulse) and 1.75 ps (deconvolved pulse) together with the TMLL with FWHM of 2.68 ps (deconvolved pulse). By using short pieces of the dispersion-compensating fiber, we were able to tune the pulsewidth of the ERGO-PGL and TMLL.

### IV. ERGO-PGL VERSUS TMLL

In order to exclude the influence of the control signal pulsewidth, the pulsewidth of the ERGO-PGL and the TMLL are matched to approximately 2.65 ps [see Fig. 2(b)].

Fig. 3 shows the measured switching windows, (integrated power of the demultiplexed signal as the relative time delay,  $\tau$ , (cf. Fig. 1) between the data and control signal is varied), when the ERGO-PGL and the TMLL are used. It is observed that the widths of the switching windows are nearly the same. The average power of the control pulses, i.e., the ERGO-PGL and the TMLL, was set to 22 dBm. Fig. 4(a) shows BER curves for the 160- to 10-Gb/s demultiplexed signal in the two cases. In Fig. 5(a), the receiver sensitivity of all 16 channels is shown when the ERGO-PGL control pulse source is used. All channels are error-free with an average sensitivity of  $-37.5$  dBm.

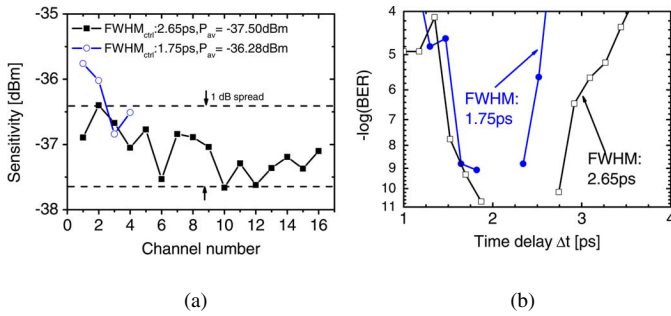


Fig. 5. ERGO-PGL is used for control signal generation and the FWHM is 2.65 and 1.75 ps, respectively. (a) Measured sensitivity. (b) BER as a function of relative time delay between data and control signal pulses.

The corresponding receiver sensitivity is  $-28.3$  dBm when the TMLL is used for control signal generation [see Fig. 4(a)]. Since the autocorrelations and the measured switching windows are nearly identical when the ERGO-PGL or the TMLL are used, this leads to the inference that pulse shape differences should not influence the measurements. Moreover, if we look at the tails of the switching windows (or the autocorrelations), it is observed that these are slightly higher when the ERGO-PGL is used. This means that the TMLL has a higher extinction ratio than the ERGO-PGL. Given that this is the case, the big difference in BER between the ERGO-PGL and the TMLL can be attributed to the higher timing jitter of the TMLL. The TMLL with 438-fs timing jitter results in a penalty of approximately 9 dB compared to the ERGO-PGL laser with 91-fs timing jitter. In Fig. 4(b), BER as a function of relative time delay  $\tau$  is plotted for the ERGO-PGL and the TMLL is used as control pulse sources. The power of the demultiplexed signal for which the measurement was performed was the power of the demultiplexed signal for which a BER of  $10^{-9}$  was obtained with an additional 3 dB. It is observed that when the timing jitter is 91 fs, we have a time-offset margin of 1.4 ps for error-free performance ( $\text{BER} = 10^{-9}$ ) compared to 0.34 ps when the timing jitter is 438 fs. Thus, as the timing jitter in the 20-kHz to 10-MHz range is increased, the requirement for the synchronization between data and control signal pulses, in order to obtain error-free operation ( $\text{BER} = 10^{-9}$ ), increases. In real transmission systems, this would mean that the clock recovery bandwidth would have to be increased in order to limit the effect of time jitter. However, increasing the clock recovery bandwidth in the presence of timing jitter (noise) may compromise its stability.

## V. INVESTIGATION FOR DIFFERENT FWHM

In this section, the ERGO-PGL is used for control signal generation and the system performance in the presence of timing jitter is investigated as the control signal pulsewidth is decreased. The FWHM of the control signal pulses takes values of 2.65 and 1.75 ps. The receiver sensitivity of the 160- to 10-Gb/s demultiplexed data signal is shown in Fig. 5(a) for the FWHM of 2.65 and 1.75 ps, respectively. The corresponding

receiver sensitivity is  $-37.5$  and  $-36.3$  dBm, respectively. Furthermore, BER curves have been measured as a function of relative time delay  $\tau$  between data and control signal pulses [cf. Fig. 5(b)]. It is observed that as the FWHM of the control pulses is decreased from 2.65 to 1.75 ps, the time delay tolerance, in order to obtain a BER of  $10^{-9}$ , decreases from 1.10 to 0.50 ps. This is because the FWHM of the data signal pulses is 1.98 ps and for the narrow control data signal pulsewidth of 1.75 ps, the effects of timing jitter become more severe due to the almost equal pulsewidth. As the control signal pulsewidth is increased to 2.65 ps, the control signal pulses are broader than the data signal pulses, thus overlapping all the time irrespective of the jitter. The switching (demultiplexing) of the data signal pulses is then less affected by the control signal timing jitter. However, the control signal pulsewidth should not become too large in order to avoid crosstalk from the neighboring channels.

## VI. CONCLUSION

The impact of timing jitter on a 160-Gb/s demultiplexer has been investigated. It has been shown that the excess timing jitter in the frequency range from 20 kHz to 10 MHz is of great importance; an increase from 91 to 438 fs leads to a penalty of 9 dB and decreases the allowable time misalignment between data and control signal pulses by approximately 1 ps. Furthermore, the impact of timing jitter can be reduced if the control signal pulses are broader than the data signal pulses.

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